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EVOLUTION OF THE UNITED STATES' SOLAR DOMESTIC HOT WATER SYSTEM RATING PROGRAM

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ABSTRACT

The Solar Rating and Certification Corporation (SRCC) has recently implemented a novel simulation-based process for generating solar domestic hot water thermal performance ratings using TRNSYS 13.1. Experience has revealed several implementation issues that have lead to increased emphasis on system testing. First, many of the certified systems have incorporated components and processes that have proven difficult to model, particularly with regard to heat exchangers, tanks, and natural convection loops. Consequently, the ability to rate all systems with literal modeling to a uniform uncertainty has been difficult to achieve. Second, the use of simulation models developed without rigid validation is not defensible, and can lead to decreased credibility. This paper summarizes these issues, and elaborates on the continuing research to produce validated models from either component based tests or whole system tests.

1. INTRODUCTION

In 1992, SRCC launched a novel, comprehensive rating and certification program (OG-300) intended to establish minimum standards for safety and reliability, and to institute a uniform system rating process (1). Ideal goals for the rating process include (2): a) allowance of different rating conditions, including annual and one-day for different solar/meteorological conditions; b) soundness and defensibility; c) minimum testing costs; d) liberal component substitution practice; and e) assistance to manufacturers in optimization of systems. Prior to the introduction of OG-300, SRCC thermal performance ratings for systems were derived from a purely empirical indoor test which satisfied only the soundness goal (3). OG-300 was intended to mostly meet all of the goals. For determining the performance ratings, the modular, component-based system simulation program, TRNSYS 13.1 (4), was chosen, because of its established library of component models, flexibility in usage, and extensibility to new components. Two premises that guided SRCC thought were: a) A survey of US industry (5) indicated that the US solar industry marketed a limited number of "generic" systems; and b) system affects could be accurately modeled if dominant components were independently characterized.

It was recognized from the onset that no single procedure was optimal. As shown in Fig. 1, two complementary paths were defined: a) component test, where the significant components' descriptive parameters are measured, and input to a generally validated simulation model; and b) system test, where the parameters of an effective system model are adjusted to fit data from a specific test protocol. The component test path has the advantage that once a model has been generally validated, only component test data are needed and system testing is unnecessary. Also, component substitution and "similar systems" (changing collector area, tank volume, etc.) can be accommodated. The major weakness in component test path is the inherent difficulty of achieving a defensible realization of "general validation." The component test path can be used only if: a) there is an exact correspondence between the real system and the model; b) the model has been generally validated; c) all component test data are available. If any of these criteria are not met, the system test path becomes necessary. The use of the system test path has the advantage that any system can be so treated; the effective model starting point need not exactly model the actual system's processes. It has the major disadvantage that strictly speaking every system must be tested. Generally, component sizes cannot be altered (for a second system rating) without re-testing. The initial expectation was that most US systems could be treated via the component test path.

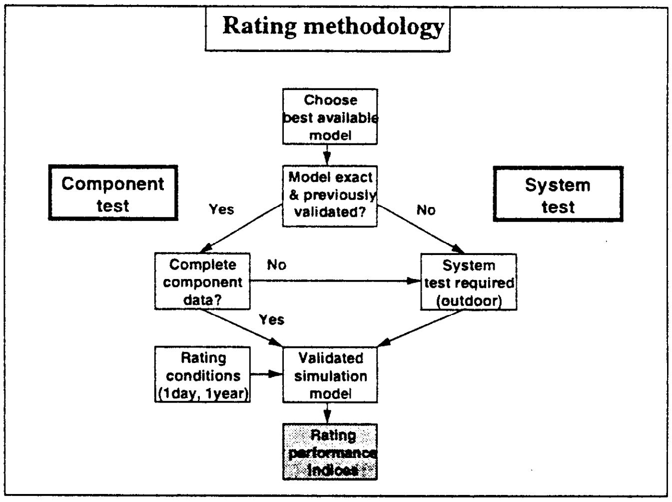

Fig. 1 SRCC Rating Paths.

2. PROGRAM EXPERIENCE

Since its inception in 1992, the SRCC TRNSYS based ratings program has produced several surprises. In reality, it was initiated before the rating process was fully developed, in response to the requirement of SRCC OG-300 certification by a major utility rebate program (6). At that time, industry submitted about fifty systems for certification, with SRCC to provide ratings. The first surprise was that these systems contained an unanticipated diversity of components, utilizing wrap-around heat exchangers, immersed coil heat exchangers, photovoltaic (PV) driven pumps, and a number of types of natural convection loops (NCL). The standard TRNSYS library did not model these components. Straightforward literal modeling was not an option. SRCC proceeded with existing models based on ad-hoc "effective" parameters, and generated ratings. A research task was also under taken to upgrade the TRNSYS capabilities, and is described in Section 3.

2.1 Component Test Path

A fundamental principle of a credible rating program is that the uncertainty associated with the rating calculations should be similar for all systems. Some "traditional" systems can be represented with validated models, with acceptable error (<10%) (7). Conversely, the uncertainty can become unacceptably large for innovative systems with non-modeled components. Attempting to model them nonetheless can cause contentious discussion as manufacturers, recognizing these uncertainties, vie for improvements in their rating (8). It has become clear that SRCC needs to enforce the principles for development of validated models to maintain its credibility, requiring system testing when the generally validated literal model does not exist. It could take many years to develop validated, literal modeling of those "innovative" systems. To maintain reasonable rating costs, new models cannot be developed for every new system type that comes along. Thus, system testing becomes the only option when generally validated literal models are not readily available. from the existing TRNSYS library.

Another surprise was that the existing modeling of supposedly well-understood components was more troublesome than originally believed. For example, as tank data were examined, it became clear that the existing approach, based on nominal insulation, geometry and conductance, was inaccurate; available data on conventional tanks showed losses roughly twice those predicted. More importantly, tank data on the systems' solar tanks were non-existent. Consequently, a rule was agreed upon that tank loss coefficients were to be doubled, until further data became available. Such modeling difficulties increase the uncertainty band compared to component test approaches.

Modeling of large numbers of systems is naturally a daunting task. A "modularized" software system was developed. The driving forces (weather, draw) are inserted at run time, reducing deck errors, creation time, and avoiding having separate decks for every validation exercise or rating condition. However it must be emphasized that the ratings derived for a specific system or set of rating conditions may not be extrapolated to other similar designs or conditions under some circumstances without introducing an unacceptable uncertainty in the result.

2.2 System Test Path

We note that the system test path is under development, focusing on outdoor tests that can be inexpensively executed. Research has been underway internationally (9 and 10) for more than a decade on this problem, and the final answers are not in. Adapting from the work in Europe, a draft SRCC model calibration and model validation process (11) is under test on three systems at Colorado State University (CSU) and two at the Florida Solar Energy Center (FSEC). Tests for both model calibration (warm-up tests) and for model validation (repeated trials, standard draw, under ranges of daily average radiation and temperature difference) are specified. The protocol is designed to elicit robust parameters by forcing the system to operate at high and low values of irradiance and system to ambient temperature difference (DT). At a minimum, the collector optical gain and thermal loss coefficients are identified using standard non-linear least squares procedures. Additional parameters (e.g., relating to tank loss and stratification) are identified for certain system types, where such modeling is considered to be weak or tank test results are unavailable.

For OG-300, SRCC has used the system test path for all the passive systems, using existent test data. Initially, a system test process was ill-defined, only limited test data (3) were available, and a different process was required. For integral-collector-storage (ICS) systems, OG-200 results include the loss coefficient and daily energy savings (or energy increase for pre-heat tests) under specific conditions. When the measured loss coefficient was combined with identification of the optical gain coefficient to match the daily savings, four days of independent outdoor data were predicted within 6% (12). A more flexible and convenient process which could be performed outdoors or indoors was demonstrated by Davidson (13) using a series of warm-up tests at different levels of irradiance and temperature difference. The parameters were identified simultaneously, and the separate loss coefficient measurement was not needed.

3. MODELING ISSUES

At the start of the OG-300 program, TRNSYS lacked several significant components that were needed to model systems. Although the system test path could be used in such cases, industry-wide benefits were expected from better fundamental models for innovative systems, and research was initiated. In this section, a summary is given of this research, including modeling work and concomitant experimental work to define tests providing the model inputs.

3.1 Passive systems

ICS Modeling. An existing finite difference model for an ICS system (14) was modified to include sky infrared affects, account for some wind affects, and allow use of biaxial incidence angle modifiers (IAM) (12). Algorithms were developed for either tubular or flat plate systems. A corresponding sky radiation model was developed to generate the necessary sky temperature input. In addition, software was developed to predict the optics of tubular systems using a Monte Carlo ray-trace approach (15). The calculated off-normal IAM were compared to measured values at two angles, and showed agreement within experimental error of about 7% (16). Work continues to simplify the geometrical inputs and upgrade the reflection model. Generally, all ICS must be tested, and the calculated IAM matrix is to be used as is; errors in calculated IAM's are subsumed in the identified value of the normal incidence optical gain parameter. [The proposed SRCC test protocol does specify conditions for high-incidence angle testing, if desired.]

Thermosiphon modeling. Although TRNSYS contained a thermosiphon component, the tank-in-tank heat exchanger used in freezing climates was not modeled. An upgrade to the original model was created at the University of New South Wales (UNSW) (17) to incorporate the tank-in-tank heat exchanger. This model has been adopted by SRCC and was normalized to OG-200 data for both one and two tank systems. This model was subjected to short-term warm up tests at CSU (18). This work indicated that the new model over predicts the stratification within the heat exchanger mantle, although the predicted collected energy is within 10% of the data. Further experimental work is being conducted at UNSW to study the stratification.

3.2 Heat Exchangers

The original TRNSYS 13.1 heat exchanger model only allowed the specification of a constant effectiveness or constant UA value to describe the heat exchanger. Currently, SRCC still uses the constant effectiveness method for evaluating most heat exchangers. The value for this effectiveness (when no direct data are available) is based upon work performed at CSU (19). However, many of the new systems utilize either PV-driven pumps or NCL with varying flow rates. In these cases, the overall heat transfer coefficient may vary significantly. A newly developed heat exchanger model using either standard correlations or empirical correlations from component testing (20) is being evaluated by SRCC for use in modeling shell and coil NCL heat exchangers. Research is underway at the University of Minnesota (UM) (21) regarding test protocols and analysis of NCL heat exchangers.

Experimental work at FSEC for doubly pumped heat exchangers has illustrated the limitations of extrapolating test data from one set of heat transfer fluids to another. Using input from the National Renewable Energy Laboratory (22), SRCC is exploring the fitting of standard heat exchanger correlations to generalize data from one fluid to other fluids.

A common component in US solar water heating systems is the solar storage tank with a supply side wrap-around heat exchanger coil. A model was developed at CSU (23) employing the Nusselt-Rayleigh correlations suggested in (24). The correlations were normalized by fitting data sets at several constant heat input levels. A constant temperature test protocol (which more efficiently stresses different DT regimes) is under development at CSU. This model with the experimental normalization factor has been adopted by SRCC for the rating of these systems. It is anticipated that the test protocol will also apply to immersed coils.

One modeling problem that has arisen is the interaction of differential controllers and the effectiveness of heat exchangers. It was discovered that when the effectiveness of a heat exchanger for a one day simulation using stepped radiation was raised, the apparent system performance fell. A study (25) indicated that the problem occurs because of TRNSYS's use of a "stickiness" factor on the controller, which allows for the simulation to continue when controller convergence criteria are not met during a time step. TRNSYS indicated no flow because the conditions were not satisfied for an entire time step. The temporary solution has been to set all of the controller lower deadbands equal to 0. The long term-solution is the use of the new controller in TRNSYS 14 which allows the controller to operate for part of the time step, thereby avoiding this problem.

3.3 <u>Storage Tank Modeling</u>

The previous stratified tank model in TRNSYS lacked many of the features needed to literally model systems "in the field" such as two heating elements, internal heat exchangers, attached loss mechanisms, non-standard fluid inlet and outlet locations, and non-cylindrical geometry. The new model (26) now accommodates these needs, allowing for more flexible usage. The previous model also yielded small energy balance errors for short-term simulations and had difficulty simulating certain open loop systems. The new model has solved these problems by using an internal time step for calculations. This model is presently being evaluated by SRCC.

One of the considerations of modeling storage tanks has been the modeling of stratification, which is related to the number of nodes. A study by Kleinbach (27) was used by SRCC as the basis for determining the corresponding number of nodes for tanks that do not contain internal heat exchangers. The procedure recommended by the IEA (28) has been proposed to replace this method, which seems to provide unreasonable predictions under some conditions.

An issue raised by the capability to model two heating elements is the respective deadbands of the thermostats. Experimentation at CSU (29) and FSEC (30) has shown that there is a great deal of variance in the deadbands of the different thermostats. These studies have also shown systematic differences in the deadbands in thermostats used at the top and bottom of standard tanks. The measured average deadbands have been adopted by SRCC.

Further tank experimentation at CSU (31), FSEC (32), and UM (33) also indicated some surprising facts regarding the observed losses from tanks. It appears that the manner in which the test is conducted can affect the inferred U-value by a factor of 2. It is believed that internal natural convection within the piping attached to the tank accounts for these large discrepancies. The intended goal of this research is to isolate the tank conduction and piping convective losses and evaluate them separately. At present SRCC has not changed these parameters due to a lack of data and uncertainty with the nominal values presently used. Further research at Arizona State University is being to conducted to quantify some of these loss mechanisms.

3.4 <u>Other Modeling Issues</u>

An important modeling parameter is the collector flowrate. Presently, SRCC uses the design flowrate specified by the manufacturer. These values are not necessarily consistent with specified pumps and system flow geometry. SRCC is developing a spreadsheet that is tailored to the needs of solar systems. This spreadsheet includes equations that predict the plumbing fitting K values, and equipment pressure drops for a range of laminar and turbulent flow rates and fluids. Some comparisons have been made with commercial software, and validation is underway. SRCC has changed the collector testing specifications to include pressure drop as a function of flow rates. In a related vein, the use of PV-pump systems is increasing. At present, a cumbersome external process is used to give collector flow as a function of irradiance. The necessary data includes the system head loss curve, PV panel performance, and pump head-flow and power relations. Work at the University of Wisconsin-Madison is being undertaken to perform such calculations internal to TRNSYS.

Another area of interest is the general modeling of any type of natural convection loop (NCL) within TRNSYS. A general NCL module was written to solve for the induced flow rate, given the friction head and average temperature in all defined flow passageways in the loop (34). Iteration is required, as both inputs depend on the inferred mass flow rate. As it is uncertain whether the NCL problem can be solved using a general NCL module, research is continuing on resolving instabilities in the solution.

4. CONCLUSIONS

The simulation-based rating process implemented by SRCC has gone through a period of evolutionary development. Modeling capability has been increased, and a number of new models and component test procedures are under development, particularly regarding heat exchangers, tank and piping losses, natural convection loops, and photovoltaic-pump combinations. Initially, there was an expectation that while a system test would be needed for some passive systems and for some innovative systems, the component test path would be most widely used, with existing TRNSYS models providing a basis for a literal model of the system. The large number of modeling issues, coupled with time delays and expense for generating new models, indicates the need for an increased use of the system test path. Simplified system validation tests are also needed, to increase confidence in the process. The SRCC rating methodology in OG-300 has proven to be as flexible and useful as envisioned. However, the notion that the majority of the systems could be modeled using literal component models has been frustrated by unacceptable uncertainties for a number of components. Thus, it is clear that in the foreseeable future, SRCC must rely on a combination of literal component models, component testing and system testing to develop performance ratings which satisfy its requirements of intercomparability, uniform uncertainty levels, and adaptability to local solar/meteorological and load conditions.

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